NASA TECHNICAL TRANSLATION NASA TT F-16, 109

CERTAIN QUESTIONS OF THE DYNAMICS OF THE FORMATION OF THE GLASS PARTICLES OF THE REGOLITH

Yu. B. Chernyak and M. D. Nusinov

(NASA-TT-F-16109) CERTAIN QUESTIONS OF THE DYNAMICS OF THE FORMATION OF THE GLASS PARTICLES OF THE REGOLITH (Kanner (Leo) Associates) 24 p HC $3.25 N75-13773
CSCL 03B G3/91 Unclas 05026

Translation of "Nekotoryye voprosy dinamiki obrazovaniya steklyannykh chastits regolita," Academy of Sciences USSR, Institute of Space Research, Moscow, Report Pr-189, 1974, pp. 1-27

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JANUARY 1975

STANDARD TITLE PAGE

1. Report No. NASA TT F-16,109	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Certain Questions of the Dynamics of the Formation of the Glass Particles of the Regolith		5. Report Date January, 1975 6. Performing Organization Code
7. Author(s) Yu. B. Chernyak and M. D. Nusinov		8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASw-2481 13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Nekotoryye voprosy dinamiki obrazovaniya steklyannykh chastits regolita," Academy of Sciences USSR, Institute of Space Research, Moscow, Report Pr-189, 1974, pp. 1-27

16. Abstract Diverse glass particles are present in large numbers in the lunar regolith, contribute to several of its specific physical characteristics, and thus are indicators of surface processes. Upon analysis, it was concluded that the condensational mechanism does not appreciably contribute to the formation of fine (10^{-1} - 10 μm) spherical regolith particles. The main cause of their formation was found to be the vibration and breakdown of liquid jets during the splashing of surface material as a consequence of meteoritic bombardment of the lunar surface. The size of the large particles is limited by some characteristic stability ($\lesssim$ 1 mm). Large spherical and elongated particles (100-500 μm) were formed during the splashing of liquid resulting from endogenic events (volcanism and so on) at significantly lower characteristic velocities.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	247	

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NASA-HQ

AUTHORS' ABSTRACT /2*

Diverse glass particles present in considerable numbers in the lunar regolith and contributing to several of its specific physical characteristics (for example, optical and others) are indicators of surface processes.

The goal of this study was to analyze the possibility of a given process occurring on the surface of the Moon and its relationship to the formation of glass particles based on the appropriate estimates. It was concluded that the condensational mechanism does not make an appreciable contribution to the formation of fine (10^{-1} - 10 μm) spherical regolith particles. The main cause of their formation is the vibration and breakdown of liquid jets during the splashing of surface material as a consequence of meteoritic bombardment of the lunar surface. The size of the large particles is limited by some characteristics stability size ($\lesssim$ 1 mm). Large spherical and elongated particles (100-500 μm) were formed during the splashing of liquid resulting from endogenic events (volcanism and so on) at significantly lower characteristic velocities.

The erroneousness of several concepts of the mechanism of particle formation found in the literature is shown. This involves, first of all, the formation of dumbbell-shaped and elongated particles that could not have been formed by rotation but were formed during the breakdown of jets resulting from linear vibrational processes. Upon collisions of secondary particles produced in meteoritic impact, generally glass particles were not formed but only their shape can undergo change (transition from regular to irregular). Equations describing the transformation of the surface material are proposed.

* Numbers in the margin indicate pagination in the foreign text.

CERTAIN QUESTIONS OF THE DYNAMICS OF THE FORMATION OF THE GLASS PARTICLES OF THE REGOLITH

Yu. B. Chernyak and M. D. Nusinov

The finely dispersed fraction of lunar surface material returned to Earth by the Luna and Apollo spacecraft contains a high (in some cases up to ~ 90 percent) content of glass particles [1, 2], whose presence characterizes clearly physical (including optical) [3] properties of the surface layers of the Moon. /3

The concepts advanced in this article show that the glass particles are also indicators of processes occurring on the surface of the Moon. Study of the dynamics of their formation must deepen our knowledge of the evolution of the surface layers of celestial bodies lacking atmospheres.

Without dwelling in detail on the geochemical characteristics of the glass particles of the lunar regolith, we present several of their physical characteristics.

1) Particles are found in the form of bodies of regular (spheres, spheroids, ellipsoids, dumbbell-shaped, sickle-shaped, fibrous, droplets, and so on) and irregular (fragments of the above-listed shapes, acute-angled particles, and so on) shapes [4].

2) The size distribution of spherical particles is bimodal (Fig. 1 a, b, c) with maxima in the region of small (10^{-1} - 10 μm) and large (100-500 μm) particles; the left maximum is consider- /4
ably sharper (Fig. 1) so that most of the particles are fine, but most of the mass is contained in large particles [4, 5, 6, 7, 8, 9, 10]. Both the left and right boundaries of the distributions have not been adequately investigated.

3) The percentage of elongated shapes increases with particle size. Thus, according to [4] there are no elongated

shapes in general among particles 1-2 μm in size, while there are only 1 percent spheroids with eccentricity higher than 0.5. Among 200-500 μm particles, spheres represent 64 percent, spheroids with eccentricity greater than 0.5 -- 11 percent, and dumbbell-shaped particles -- 4 percent.

4) The ratio between the total amount of glass and nonglass particles and also between glass particles of regular and irregular shape changes appreciably from area to area. Thus, for the dust returned by Apollo 11, the total number of glass particles represented ~ 50 percent (of these there were approximately 20 percent of spherical shape), glass particles returned by Apollo 12 -- 20 percent (~ 1 percent of these were spherical), glass particles returned by Luna 16 -- 25 percent ($\sim$ 1-1.5 percent of these were regular in shape), glass particles returned by Luna 20 -- 10 percent (of these $\leqslant 1$ percent were spherical) and, finally, the total number of glass particles for the "orange" soil returned by Apollo 17 was ≈ 90 percent (most of these were sperical) /11, 12, 13, 14, 15, 16, and others/.

5) Large numbers of the glass particles were coated with dustlike particles /17/.

6) In lunar dust monomineralic glasses (anorthite, olivine, and pyroxene) were found, compositionally close to the composition of lunar minerals /17/.

7) The mean density of the lunar glasses was close to $\rho = 3.0$ g/cm^3 and only for individual particles saturated with gases was it reduced to $\rho = 2.5$ g/cm^3 /17/.

MacKey /17/ points to the following mechanisms of glass sphere formation due to exogenic and endogenic processes: /5

a) expansion and rupture of large masses of molten glass formed around the center of main impacts;

b) breakdown of shock-formed liquid jets into chains of droplets;

c) splashing and reflection from objects of colliding molten glass;

d) deceleration of splashed glass at solid surfaces;

e) condensation from vapor; and

f) forming of volcanic or shock-formed magma.

These mechanisms are also referred to in papers by Tolansky, Buettner, Zel'dovich and Rayzer, Florenskiy et al. /18-21/.

In a number of studies it is noted that one cause of the formation of glass particles may also have been collision with the lunar surface of secondary particles generated during a meteoritic impact /17/.

Papers by Pugh /22/ and also Carusi et al. /23, 24/ examined a rotational mechanism of the elongation of glass particles formed during meteoritic impact.

Gold /25/ believes that in addition to vitrification of surfaces in craters, glass spherules may also have been formed on the surface of the Moon (see Muller and Hinch /4/). On the other hand, Mills /26/ discusses the possible formation of glass droplets during the venting of gases through the molten surfaces of the lunar layers. Experimental simulation of several glass /6
particle forming processes was conducted by Cloud /6/, Nusinov et al. /9/, Florenskiy et al. /21/, Gross /27/, Blander et al. /28/, Fox et al. /29/, and others.

This study analyzes several questions of the dynamics of glass particle formation during exogenic and endogenic processes in order to understand which of the mechanisms in principle is possible and which are dominant.

2. Analysis of Size Distribution of Regolith Particles

Let us first look at processes occurring during a meteoritic impact: vaporization followed by condensation and splashing of the molten material of the lunar regolith. Upon mechanical crushing, the glass particles are not formed owing to their low specific energy ($\sim 10^9$ erg/g) of this stage of the process (melting energy $\sim 10^{10}$ erg/g [20]).

Each of the first two processes can lead to the formation of particles with the characteristic dimensions r_1 and r_2, proportional to the first approximation to the size of the initial regolith $R = k_1 r = k_2 r_2$. (1)

Eq. (1) will remain valid all the way to some value r_{st}, which is the characteristic stability dimension and which in our view is related to the mode of distribution.

The contemporary size distribution of meteoritic matter [30] yields a maximum corresponding to $\sim$ 2-1 μm (masses $\sim 10^{-11}$-10^{-12} g).

If we use the f(m)-differential mass distribution function /7
of meteoritic material, the numbers of primary particles with masses in the range m to m + dm is

$$dN = f(m) \cdot dm. \qquad (2)$$

Since $m = 4/3(\pi\rho R^3)$ and $dm = 4\pi\rho R^2 dR$ for spherical particles, the number of primary particles with dimensions from R to R + dR will be

$$dN = f\left(\frac{4\pi}{3}\rho R^3\right) \cdot 4\pi\rho \cdot R^2 \cdot dR,$$

that is, the size differential distribution function of these particles will be

$$F(R) = f\left(\frac{4\pi}{3} \cdot \rho \cdot R^3\right) \cdot 4\pi\rho \cdot R^2. \qquad (3)$$

Using Eqs. (1) and (3), let us find the differential function Fi(2) of the distribution of secondary (condensed i = 1 or splashed i = 2) particles

$$F_i(r) = A_i f\left(\frac{4\pi}{3}\rho \cdot K_i^3 r^3\right) \cdot 4\pi \cdot \rho \cdot K_i^3 \cdot r^2 \quad i = 1, 2 \qquad (4)$$

where Ai is the normalizing constant, whose exact value is not significant for our purposes.

By comparing (3) and (4), we see the similarity of the distributions, differing only in the scale factors K_i^{-1} along the X-axis and Ai -- along the Y-axis.

Using the results of calculating condensation kinetics reported by Zel'dovich and Rayzer /20/ for the estimates, for the condensation mechanism we get Ki $\cong 10^3$. For splashing, from the experiments reported in /19/ we obtain the currently updated value $K_2 \cong 5\text{-}10$. These values for splashing give $0.1 \leqslant 2r_1 = d \leqslant 1$ μm for the region of the micrometeorite distribution maximum, and $1 \cdot 10^{-3} \leqslant 2r_2 \leqslant 5 \cdot 10^{-3}$ μm for the conditions of condensation from the vapor phase. Thus, the condensate particles generally have sizes of nearly atomic order.

This distribution (Fig. 1) must be cut-off at the left, /8 in the region of small particle sizes in view of particle cohesion, a consequence of the van der Waals intermolecular interaction. Let us use the following arguments to estimate the minimum sizes of the cohering aggregates of glass particles: the actual microscopic strength under the cohesional mechanism of bonding between particles δ_m will be determined only by the finest particles, since large particles have a low effective surface of interaction.

Let us further assume that the microscopic strength δ_m, whose value is determined by measuring the cohesion of the lunar regolith, is caused, according to the simplest model by the van der Waals interaction of the spherical microscopic particles in contact with each other along the surface of elementary contact S_o.

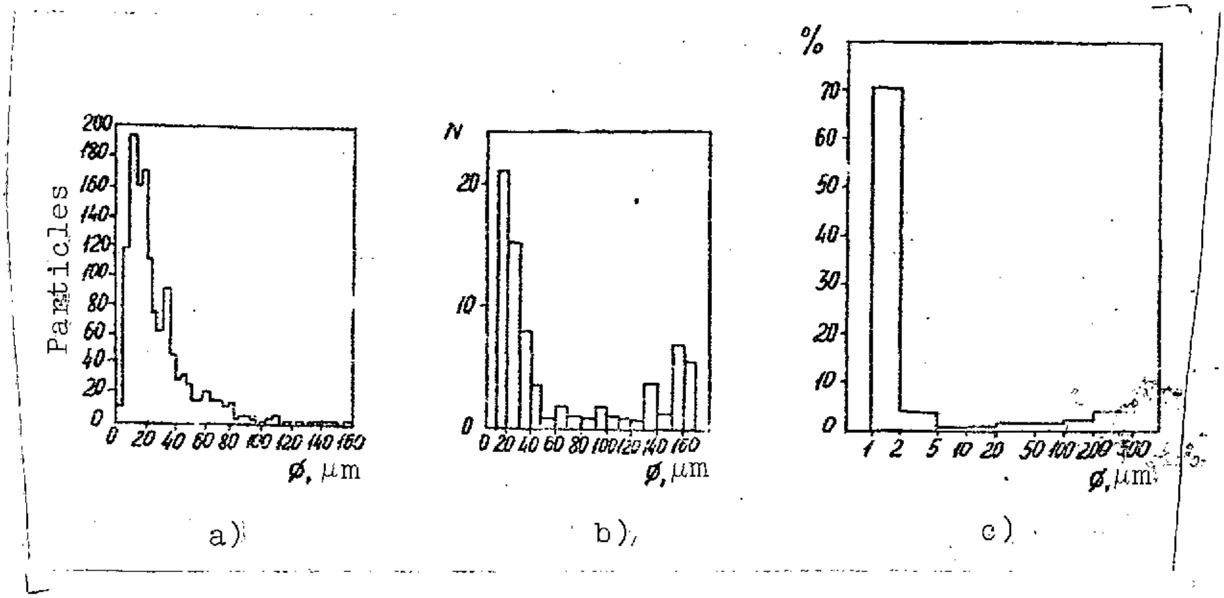

Fig. 1. Typical particle size distributions
a) [6]
b) [5]
c) [4]

If n is the number of these particles with diameter d fitting onto the area 1 cm^2, then $n \sim 1/d^2$. Obviously, the force needed to separate this layer with an area 1 cm^2 will be

$$\boxed{\sigma_m = S_0 \cdot \sigma_t \cdot n,} \tag{5}$$

the quantity S_o is determined by the characteristic radius of intermolecular interaction, of the order of $\sim 10^{-8} - 10^{-7}$ cm.

$$\boxed{S_0 = \pi \cdot r_m^2.} \tag{6}$$

Specifying the values of S_o, δ_t, and δ_m, let us determine from (5) n and therefore also d:

$$d \sim 2\ \mathrm{cm} \cdot \sqrt{\frac{\sigma_t}{\sigma_m}} \tag{7}$$

It is known that for lunar regolith $\delta_m \sim 5 \cdot 10^3 - 5 \cdot 10^4$ dynes/cm^2 /31, 32/, and $\delta_t \sim 10^9$ dynes/cm^2 /33/. Hence, by Eq. (7) $d \sim (0.5-2) \cdot 10^{-1}$ μm = $(0.5-2) \cdot 10^{-5}$ cm. Therefore, the finest glass particles formed under the condensational mechanism can either soon aggregate together into larger formations or adhere to larger foreign particles. The formation of charges on droplets of atomized liquid can also be one of the reasons for this adhesion: these particles will be drawn to the "grounded" particles on the lunar surface, thus inducing a charge with opposite sign in them. /9

These arguments can be supplemented by the results of laboratory experiments estimating the minimum sizes of lunar regolith glass particles and also glass particles of basalt condensate obtained in vacuum by blowing gaseous helium and also without this treatment /34, 35/.

From these experiments it follows that condensate without blowing has the highest dispersion. The specific surfaces determined by the Brunauer-Emmett-Teller method have the following values: $S \sim 10^2$ m^2/g for the basalt condensate (according to the formula $S \cong \delta / \rho \cdot \ell$ (8), /36/) and particle size $2 \cdot 10^{-6}$ cm; condensate with blowing, $S = 5 \cdot 10^{-1} - 10$ m^2/g, $r = 2 \cdot 10^{-5} - 5 \cdot 10^{-4}$ cm, and dust fraction of Luna-16 lunar regolith $r = 4-5 \cdot 10^{-4}$ cm /34/. This method gives us only the lower estimate, since it does not differentiate individual particles and mixed aggregates with the surface developed for gaseous sorption.

These considerations suggest the conclusion that the condensation mechanism as such cannot be responsible for the formation even of regolith glass particles corresponding to the smaller distribution mode.

3. Splashing Process

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From the fact that small glass particles of the left mode cannot be formed from the vapor phase it follows that they are formed from the liquid phase. In the general case the formation of glass particles from the liquid phase is a splashing process occurring both during a meteoritic impact as well as during the foaming of volcanic magma. During splashing individual masses of liquids of different shapes will be formed: in the form of jets, spherical droplets, and other intermediate shapes. Since the particles form in a vacuum, the only perturbations leading to changes of their shape can be the perturbations induced in the process of particle initiation. The different elements of liquid droplets acquire different velocities and thus necessarily have internal motions, and do not move as solids. Their shapes are unstable and will undergo further evolution, a consequence of the opposition between forces of inertia and surface tension /37/.

Let us first look at the case when the inertial forces are sufficient to collapse the liquid mass. In this case, regardless of shape, we can state that

$$\rho \frac{\bar{v}^2}{2} \geq K \frac{\sigma}{r} \qquad (9)$$

where the dynamic pressure $\rho \cdot (\bar{v}^2/2$ is determined by the mean velocities of the internal mostions of the liquid, the coefficient K = 1 corresponds to a cylindrical jet and K = 2 -- a spherical mass, and in the general case $1 \leqslant K \leqslant 2$.

From Eq. (9) it follows that the characteristic stability size r_{st} (when $r > r_{st}$, collapse occurs) is

$$r_{st} \approx \frac{2K\sigma}{\rho \bar{v}^2} . \qquad (10)$$

From (10) it is clear that this processes associated with the high velocities of internal motions always lead to the formation of small particles. Let us relate the velocity of internal motions v with the microscopic perturbing velocity u of the mass overall in the following form: /11

$$\tilde{v} \sim u \cdot \frac{\lambda}{\ell} \cdot \tag{11}$$

where ℓ is the characteristic size of the perturbed region (thickness of ejected jet, and so on). From (10) and (11) we get a rough estimate for r_{st}:

$$r_{st} = \sqrt{\frac{\varepsilon K \sigma}{\rho}\left(\frac{\ell}{u}\right)^2} \cdot \tag{12}$$

Using (12), we can easily calculate that in the range of velocities and sizes characteristic of meteoritic impact (even for very large meteorites), all the particles formed fall in the region of the left mode of the size distribution ($r_{st} <$ < 10 μm).

Therefore the observed ($r \sim 0.5$ mm) particles can be formed only due to small endogenic (volcanic and so on) processes. Hence it follows, in particular, that large particles corresponding to the right mode must be much "older" than the fine particles.

Now let us examine the case when the kinetic energy of the internal motions of a particle is insufficient for its collapse. This situation will be observed after the culmination of the possible disintegrations. In this case vibrations of the droplet are induced, dying out under the effect of viscosity forces.

Let us examine in more detail the vibration of a droplet that is spherical at the initial moment and that has some internal motions. As a result of these motions, after some interval of time it can be elongated. Since the pressure of surface tension /12

$P_\rho \sim 1/2$, at the ends of the droplet resultant forces are induced, striving to return the droplet to spherical shape. Then the process is repeated in the perpendicular direction.

The condition for the existence of vibrations must be

$$\tau_s \gg T, \tag{13}$$

where τ_s is the characteristic cooling time, and
T is the period of vibrations.

We can regard a liquid glass particle as a linear oscillatory system. The parameters of this system will be as follows: ω_o is the natural frequency of vibrations; $\omega_o = 2\pi/T$ (14), where T is the period of vibrations determined by the Rayleigh formula /38/: $T \sim \sqrt{\rho v/\delta}$ (15); γ is the decrement of damping, which from dimensional considerations is $\gamma = \;/\rho d^2$ (16); and ν is the viscosity of liquid.

If the initial state of the particle is assumed to be undeformed, while the perturbation is assumed to be the initial velocity equal to the characteristic rate of the process, its linear vibrational equation can be written as

$$\ddot{X} + 2\gamma\dot{X} + \omega_o^2 X = 0. \tag{17}$$

X can be interpreted as the characteristic elongation of the droplet. Strictly speaking, X is the Fourier coefficient of expansion of the particle shape equation in Legendre polynomials. The solution of Eq. (17) for $\omega_o > \gamma$ will be vibrational in nature:

$$X \simeq X_0 \cdot e^{-\gamma t} \cdot \sin(\omega t + \delta), \tag{18}$$

where

$$\omega = \sqrt{\omega_o^2 - \gamma^2}. \tag{19}$$

From the condition $(\omega/\gamma > 1)$, and also (15) and (16), we get

$$d > \frac{\nu^2}{\sigma \cdot \rho}.$$ /13

This condition is rapidly violated upon cooling, owing to the exponential rise in viscosity with temperature.

Let us show that the percentage of finite elongated shapes will increase with particle size. To do this, on inspecting a large number of particles (ensemble) we note that the phase δ in (18) is a random variable.

The degree of elongation of a particle e at the moment t can be defined as the value x^2 that is the root mean square value in the phase δ

$$e^2 = \langle x^2 \rangle_\delta = \frac{x_0^2}{2} \cdot e^{-2\gamma t} \tag{20}$$

Here we will assume that at some instant $t = t_s$ viscosity rises sharply and subsequently the particle "remembers" its shape.

Since t_s is determined by surface cooling of the particle, then as we can easily see $t_s \sim d$; on the other hand, $\gamma \sim d^{-2}$, therefore at the instant of time $t = t_s$ and further $\gamma t = \gamma \cdot t_s \sim \frac{const}{d}$. Therefore:

$$e = \frac{x_0}{\sqrt{2}} \cdot e^{-\frac{const}{d}} \tag{21}$$

Thus, the mean elongation of particles depends strongly on size, falling off with decrease in size, which is also observed in lunar material /4/.

4. Critical Comments on the Probability of Certain Processes Occurring on the Moon

According to the widely held viewpoint /17/, during meteoritic impacts slow processes of splashing can occur in "puddles" and "lakes" of shock-molten magma at the bottom of a crater. We will show that accumulations of molten masses during impacts will /14
practically speaking never occur.

The velocity U of a medium behind a shockwave is associated with the specific energy ϵ in the same region by the relation $\epsilon \sim U^2/2$. Fusion will occur when the condition $\epsilon \gg \epsilon_m$ is satisfied. Therefore,

$$U \simeq \sqrt{2\epsilon_m} \tag{22}$$

When $\epsilon_m \sim 5 \cdot 10^9$ erg/g [20], $U \sim 10^5$ cm/sec. Therefore the molten liquid will be ejected at high velocities from the crater. Only at the sites of contact of the liquid with the crater sides (that is, in the zone of the hydrodynamic boundary layer) will the velocities of the molten liquid mass be small and capable of leading to vitrified surfaces forming.

Let us clarify the possibility of the near-wall boundary layer of molten liquid forming in a crater during shock processes.

To do this, we will first show that the liquids that can remain within the crater must either be in the near-wall boundary layer, whose thickness we will next estimate. To do this, let us first calculate the order of magnitude of the Re number for near-wall motion of the liquid:

$$Re = \frac{U \cdot D_p \cdot \rho}{\nu} = D_p \cdot \frac{5 \cdot 10^5 \text{ cm} \cdot 2}{10^3} \simeq 10^3 \cdot D_p ,$$

where D_p is the diameter of the molten part of the crater ("pits") (in centimeters), which is associated with the crater D_s ("fragmentation zone") by the relation $D_p \sim D_s/5$ [39]. For the estimate, let us assume $\frac{D_s}{D_p} \simeq 10$, $\nu \sim 10^3$ poises; $\rho \sim 2\text{–}3$ g/cm^3 [37], ν is viscosity of liquid, and ρ is density of liquid.

Hence it follows that for $D_s > 1$ mm, $Re \gg 1$, and the flow will occur with a boundary layer having the thickness [40]

$$\delta_0 \simeq \frac{D_p}{\sqrt{Re}} \simeq 10^{-2} \cdot \sqrt{D_s} . \tag{23}$$

Therefore, even for craters with D_s = 100 m and D_s = 10 cm, /15
we get the values δ_o = 1.0 cm and 0.3 mm, respectively.

Clearly, a layer 0.3 mm thick will in general not flow along rough ground, but a layer with δ_o = 1 cm can for a 100-meter crater, in the best of cases, be formed in the streaming of a puddle with a depth of $\sim$ 30 cm.

These figures give a severely overstated estimate, since the external sections of the boundary layer will travel at greater speeds and upon collision will be ejected out of the crater zone. These ejecta, as earlier stated. will have the form of jets breaking down into individual droplets.

Further, let us turn to the rotational mechanism of the formation of elongated particles examined in a number of papers /22, 23, 24/ and others. We note that rotational motion can be realized only in the boundary layer when there are large velocity gradients, of the order of $\omega \sim |\mathrm{grad}\ \vec{\gamma}| \sim |\mathrm{rot}\ \vec{v}|$. Since the near-wall layer is thin, clearly the fraction of this liquid is low. Only liquid that is in the outer section of the boundary layerwwill be ejected with rotation.

Let us show that when rotation is present, the ejected particles will acquire an S-shaped form.

The calculations of shapes of elongated particles that can be formed when liquid masses are rotated, presented in /22, 23/, were based on an analysis of statistically equilibrium droplet shapes in a rotational system of coordinates. But the actual formation of elongated shapes occurs when the liquid moves within a droplet. These motions must necessarily give rise to
Coriolis accelerations /41/, which, in the statistical approach, /16
are no longer inconsideration because it is inappropriate.

Let us estimate the transverse flexion S of a particle that is spherical initially and elongated in length 2ℓ in the final state. If the time of elongation of this particle is τ, the characteristic elongation rate will be $v = \ell/\tau$. In longitudinal motion, a Coriolis acceleration equal to a_1 = /illegible/ $\omega\gamma$ is induced. The transverse deformation S will be $S = a_{II}\tau^2/2$ and, therefore,

$$\frac{S}{\ell} = \omega \cdot \tau \tag{24}$$

On the other hand, the longitudinal displacement occurs under the effect of the resultant stretching centrifugal force of inertia and the restoring force of surface tension. We only reduce S/ℓ if we neglect the viscosity and the surface tension. Let us set $a_{II} \cong \omega^2 \ell$. Hence /illegible/ $a_{II} \cdot \tau^2/2 \approx (\omega\tau)^2 \ell/2$ and, thus, $\omega\tau \approx \sqrt{2}$ and, therefore, $S/\ell > 1$.

Thus, for elongated shapes this ratio is larger than 1 and the estimate indicates that bending is very intense.

Only the kinematic characteristics were used in these estimates and the estimates are wholly independent of the other physical constants.

On the other hand, when a particle with two displaced centers of mass inhomogeneity with characteristic radii of curvature r_1 and r_2 is rotated about the longitudinal axis, the pressure of surface tension will be $\rho_1 = 2\delta/r_1$ and $\rho_2 = 2\delta/r_2$ and, therefore, liquid will stream from the region of higher pressure to the region of lower pressure, that is, from the region of lesser inhomogeneity to the region of greater. This configuration therefore is unstable and will not form dumbbell-shaped particles.

Thus, the rotational mechanism cannot lead to the formation axisymmetric particles. But bent particles (sickle-shaped) observed in lunar dust most likely were formed by rotation. /17

Let us further examine the problem of the possible formation of glass particles of regular shape upon the collisions of secondary meteoritic particles. The velocities of secondary particles cannot exceed the escape velocity for the Moon ($V_e \cong 2.4$ km/sec), and the velocities of most secondary particles are in the interval $v \ll v_e$ ($v \sim 10^2$ m/sec) /42/.

The corresponding specific energy in the shockwave induced by the collision of secondary particles is $\sim v^2$//illegible/ /20/, which gives a value at the escape velocity of $\sim 5 \cdot 10^9$ erg/g /20/, that is, it lies at the boundary of the specific heat of melting, which is insufficient for melting and vitrification if one considers that part of this energy must be expended in several subsidiary mechanical processes during cratering.

Therefore, during secondary meteoritic collisions no glass particles are formed, but upon impacting against glass, only changes in particle shape can occur (transition from regular to irregular).

As a result of this systematic bombardment, there will be a continuous change in the ratio between glass particles of regular and irregular shape, and also between glass and nonglass masses.

From the foregoing it follows that meteoritic impact is the primary process of vitrification for fine particles, and endogenic processes are dominant for large particles.

5. Transformation Kinetics of Lunar Surface Material /18

Let us examine further how the temporal evolution of glass on the lunar surface occurred in some layer of depth h due to meteoritic impacts.

Based on arguments that are standard for physicochemical kinetics, we obtain for the mass fractions μ_1 of undeformed material, μ_2 of mechanically crushed material, μ_3 of mechanically crushed glass, and μ_4 of glass of regular shape (all the variables are given with respect to the mass Mh in a layer with depth h and per unit area), the following system of differential equations:

$$\frac{d\mu_1}{d\tau} = -(\alpha + \gamma)\mu_1 , \tag{25}$$
$$\frac{d\mu_2}{d\tau} = \gamma\mu_1 - \alpha\mu_2 , \tag{26}$$
$$\frac{d\mu_3}{d\tau} = \beta\mu_4 - \alpha\mu_3 , \tag{27}$$
$$\frac{d\mu_4}{d\tau} = \alpha(\mu_1 + \mu_2 + \mu_3) - \beta\mu_4 , \tag{28}$$

where τ = A·t is the dimensionless time on a geologic scale (compare Eq. (2)).

$$A = \int \frac{M_{crat}}{M_h} f(m)\, dm \quad [sec^{-1}] \tag{29}$$

c is the relative volume of the "pit"[1] of the crater,

β is the relative volume of the "halo"[1] of the crater, and

γ is the relative volume of "fragmentation zone"[1].

Here, $\alpha \sim 10^{-2}$; $\gamma \sim 1 - \alpha$; $\beta \sim \gamma \sim 1$. The solution of these equations are on the simplest assumption that at some initial moment there was only the uncrushed material μ_1 (0) = 1, and /19
μ_2 (0) = μ_3 (0) = μ_4 (0) = 0, we obtain (also considering $\beta = \gamma$):

$$\mu_1 = e^{-\tau}, \tag{30}$$
$$\mu_2 = e^{-\alpha\tau}[1 - e^{-\gamma\tau}], \tag{31}$$
$$\mu_3 = \gamma - e^{-\alpha\tau} + \alpha \cdot e^{-\tau}, \tag{32}$$
$$\mu_4 = \alpha(1 - e^{-\tau}), \tag{33}$$

Hence it follows that (Fig. 2) the amount of primary material drops off rapidly to zero due to fragmentation and remelting.

The amount of crushed primary material initially rises nearly to 1, and then drops off slowly due to remelting.

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[1] The terms "pit" and so on were taken from /39/.

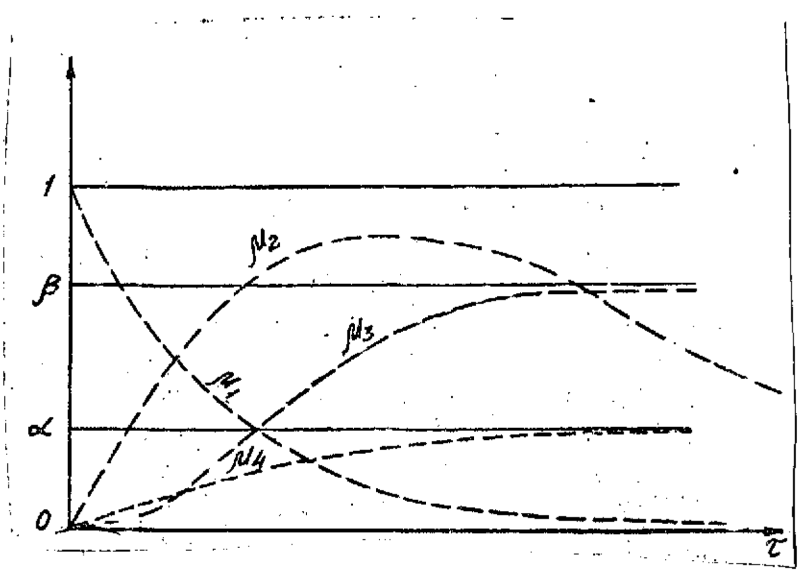

Fig. 2. Curves of the transformation kinetics of surface material

The amount of remelted glass of regular shape rises rapidly to saturation equal to α.

The amount of fragmented glass gradually increases at first slowly, and then rapidly to a saturation equal to γ.

Thus, for long periods of geologic time, all the material proved to be in the form of glass with regular and irregular shape with constant ratio of proportions equal to α/γ. Therefore, the difference in these ratios of fractions observed on the Moon for different areas is chronological characteristic of the different formations. The fact that as the end results of evolution only glass will remain on the surface indicates the importance of studying the dynamics of glass formation.

Conclusions /20

1. The condensational mechanism cannot be responsible for the formation of glass particles in the first and second size distribution modes. Formation of extremely fine ($< 10^{-3}$ μm) glass particles is most probable by means of vapor phase condensation.

2. Glass particles formed from the liquid phase during its splashing. These processes can occur both during meteoritic impact as well as during volcanic effects.

3. Formation of the smaller number of left-mode particles is entirely accounted for by high-speed processes, that is, by the interaction of meteoritic material against the lunar surface. The formation of more right-mode particles can be accounted for by endogenic processes with lower rates of internal motions (in particular, during different volcanic effects). On this basis, large particles are more ancient compared to the primary number of fine particles.

4. The main mechanism of the formation of glass particles of regular shape (spherical and elongated) is the breakdown of jets and the vibration of particles of the liquid glass mass resulting from the opposition of inertial to surface tension forces.

5. The rotational mechanism cannot account for the formation of elongated (including dumbbell-shaped) particles in view of the fact that here, owing to the Coriolis accelerations, the particles must have an S-shape, which is not observed in actuality.

6. Secondary meteorites upon collisions with the lunar /21
surface, owing to the low specific energy of the process in general do not generate glass particles but only cause mechanical fragmentation of the glass particles present.

7. During meteoritic collisions, "puddles" and "lakes" of molten material are not formed, and only small sections of vitrified surfaces can be formed in craters.

8. The continuing interaction of the lunar surface with meteoritic material must lead to the total transformation of the surface material in the glass. The ratios between the amount of glass and the remaining material and also between the glass particles of regular and irregular shapes observed over different areas of the Moon serve as their chronological characteristics.

The authors are grateful to G. A. Leykin, A. V. Ivanov, and L. V. Leont'yev for discussions.

REFERENCES

1. Vinogradov, A. P., Geokhimiya 3, /page not given/ (1971).
2. Science 165/3899, (1969); 167/3923, (1970).
3. McCord, T. B., and Adams, J. B., Science 178/4062, (1972).
4. Muller, D., and Hinch. G., Nature 228/5268, (1970).
5. Shima, M., Jabyki, H., Okada, A., and Jabyki, S., in: COSPAR Space Research, Vol. 12, Academic-Verlag, Berlin, 1972.
6. Cloud, /illegible/, Margolis, S. et al, Science 167/3918, (1970).
7. Scarlett, B., and Buxton, R. E., Earth and Planetary Science Letters 22, 177-187 (1974).
8. Jaffe, L. D., and Strand, J. N., Nature Phys. Sci. 241/ Jan. 15, (1973).
9. Nusinov, M. D., Florenskiy, K. P. et al., Doklad Akad. Nauk. 202/4, (1972).
10. Shvidkovskaya, T. Ye., Leykin, G. A., and Krasnopol'skiy, V., Report Submitted to the 13th Plenary Meeting of COSPAR, Leningrad, May 1970.
11. "Preliminary examination of lunar samples from Apollo 11," Science 165/3899, (1969).
12. "Preliminary examination of lunar samples from Apollo 12," Science 167/3923, (1970).
13. Ivanov, A. V., Rode, O. D., Stakheyev, Yu. I., and Florenskiy, K. P., in the collection: Lunnyy grunt iz Morya Izobiliya /Lunar regolith from the Sea of Fertility/, Nauka Press, Moscow, 1974.

14. Tarasov, L. S., Florenskiy, K. P., Ivanov, A. V., and Rode, O. D., Geokhimiya, 9, (1973).

15. Sky and Telescope 45/3, (1973).

16. Ivanov, A. V., Stacheew, Jr. L., Tarasov, L. S., and Florenskiy, C. P., Physics of the Earth and Planetary Interiors 7/4 [year not given].

17. Mason, B., and Melson, W., Lunnyy porody [Lunar Rocks], Mir Press, Moscow, 1973. /23

18. Tolansky, S., Endeavour 29/108, (1970).

19. Buettner, K. J. K., and Le Mo[illegible], Margaret, Die Naturwissenshaften 2/Feb. 10, (1970).

20. Zel'dovich, Ya. B., and Rayzer, Yu. P., Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniy [Physics of Shockwaves and High-Temperature Hydrodynamic Effects], Nauka Press, 1966.

21. Florenskiy, K. P., and Ivanov, A. V., Meteoritika 30, (1970).

22. Pugh, M. J., Nature 237/May 19, (1972).

23. Carusi, A., Coradini, A., Ful[illegible]hignoni, M., and Magni, G., in: "IAU Symposium, No. 47 held in England 1971, D. Reidel Publishing Co., Dordrecht, Holland, 1972.

24. Bastin, J. A., and Volborth, A., Icarus 21, 112-120 (1974).

25. Gold, T., Science 165/3900, (1969).

26. Mills, A., Nature 224/5229, (1969).

27. Gross, S. A., Nature 233, 185-186 (1971).

28. Blander, M., Keil, K., Nelson, L. S., and Skaggs, S. R., Science 170/3956, (1970).

29. Fox et al., Science 167, (1970).

30. McDonnell, J., "Report submitted to the 13th Plenary Meeting of COSPAR," Leningrad, May 1970.

31. Jaffe, L. D., The Moon 8, 58-72 (1973).

32. Cherkasov, I. I., and Shvarev, V. V., Issledovaniya po mekhanike lunnykh gruntov, provedennyye v SSSR. Spetsial'naya lektsiya na VIII Mezhdunarodnom kongresse po mekhanike gruntov /Studies on the Mechanics of Lunar Surface Materials Conducted in the USSR, Special Lecture at the 8th International Congress on Soil Mechanics/, Moscow, 1973.

33. Salisbury, J. W., Glasser, P. E., Stein, B. A., and Vonneguth, R., Journ. Geophys. Res. 69/2, (1964).

34. Kotchnev, V. A., and Nussinov, M. D. et al., in: COSPAR Space Research, Vol. 13, Academic-Verlag, Berlin, 1973.

35. Nusinov, M. D. et al., Sovremennyye predstavleniya o Lune /Modern Ideas of the Moon/, Nauka Press, Moscow, 1972.

36. Gregg, S., and Singh, K., Adsorbtsiya, udel'naya poverkhnost', poristost' /Adsorption, Specific Surface, and Porosity/, Mir Press, Moscow, 1970.

37. Nussinov, M. D., Nature, 11223, (1972); ibid, Pugh, M. S.

38. Strett, J. (Lord Rayleigh), Teoriya zvuka /Theory of Sound/, Vol. II, OGIZ GITTL, Moscow-Leningrad, 1944.

39. Herz, F., Hartung, D., and Gault, D., Earth and Planet. Sci. Lett. 10, 381-386 (1971).

40. Schlichting, H., Teoriya pogranichnogo sloya /Boundary Layer Theory/, IL Press, 1956.

41. Landau, L. D., Akhiyezer, A. I., and Lifshits, Ye. M., Mekhanika i molekulyarnaya fizika /Mechanics and Molecular Physics/, Nauka Press, Moscow, 1969.

42. Neukum, G., Me/illegible/ et al., Earth and Planetary Science Letters 8/31, (1970).